Ultrasonic signal processing method and applications thereof

The invention relates to an ultrasonic signal processing method, in particular for ultrasonic measurement devices such as flow meters. More particularly, a signal processing technique is disclosed for improving the signal-to-noise ratio in ultrasonic measurement

5   devices that operate in a noisy environment, for example ultrasonic flow meters in the vicinity of a pressure reducing valve.

Ultrasonic gas flow meters measure the gas flow by means of ultrasonic signals. For this purpose an ultrasonic gas flow meter has one or more acoustic paths, each path being defined between a pair of

10   ultrasonic transducers. Each transducer of such a pair is capable of transmitting signals to, and receiving signals from the other transducer. When operating, both transducers in turn transmit and receive, resulting in an acoustic signal that travels along the acoustic path - either parallel or at an angle - inside the meter

15   body with the flow direction (downstream) and against the flow direction (upstream). The difference in travel time for both transmission directions is proportional to the gas velocity. In order to measure even low gas velocities accurately, the travel times itself or the difference in travel time need to be measured with very

20   high accuracy and resolution in time.

Typically, ultrasonic gas flow meters operate using a number of short bursts of high frequency signals (for example 5 cycles long). Typically, the operating frequency of ultrasonic transducers is in the range between 50 kHz and 500 kHz. As in ultrasonic gas flow

25   meters differences in travel times need to be measured extremely accurately, a very high definition or resolution in the travel time measurement is a must. This cannot be achieved by using the envelope of the received burst signal, even if this is a short one. In order to obtain sufficient resolution, the exact time of the zero crossings

30   in the burst signal is required. As typically multiple zero crossings are present in the burst signal, this creates the problem of

used as reference point(s) for the travel time measurement. This may be resolved with the aid of the shape of the envelope of the burst signal.

5   In a gas pipeline, ultrasonic noise may be emitted from various other sources. The frequency spectrum of such noise may extend into the frequency range where the ultrasonic transducers operate. Such noise may be flow induced noise, or equipment induced noise, such as noise emitted by pressure reducing valves. The latter type of
10 interfering noise is more severe, especially when such pressure reducing valves operate at high pressure differentials, for example above 10 or 20 bar. Under these circumstances the amount of dissipated energy can be quite substantial. Even if only a very small fraction thereof is converted into acoustic energy, still a serious
15 amount of noise may be emitted.

        The noise from such valves may be characterised by having some dominant peaks at discrete (low) frequencies, but more appropriately it is described as broadband noise. The envelope of the frequency spectrum typically has a maximum in the range between 30 kHz and 80
20 kHz. This indicates that even outside this frequency range substantial amounts of ultrasonic energy may be present.

        The same holds for valves that have been designed to be so-called "silent valves". The word "silent" typically applies to the noise in the audible range. Sometimes reduction of noise in the
25 audible range is achieved by design modifications that shift the emission of noise to higher frequencies. As this noise is broadband by nature, it easily extends into the frequency range where ultrasonic transducers for ultrasonic gas flow meters may operate.

        Due to practical limitations the power of the signals used in
30 an ultrasonic flow meter is restricted to certain levels. The problem arises that either the noise interferes with the ultrasonic signals of the flow meter, or the ultrasonic signals of the flow meter may even become completely buried or masked by the noise. As a result of this the ultrasonic signals used by the flow meter may become
35 undetectable and therefore the meter may become un-operational.

        Until now in various ways, attempts have been made to resolve

ultrasonic flow meter.

Attempts have been made to resolve the problem of acoustic
noise interfering with the signals of an ultrasonic flow meter by
5   separating the ultrasonic gas flow meter and the noise source
spatially. This means separating the two by applying a long length of
pipe, preferably also including elbows and T-bends, between the meter
and the noise source. As available space does not always allow for
such an approach, this method may not only be costly but often is
10 impractical as well.

Moving the operating frequency of the flow meter away from the
frequency range of the ultrasonic noise has also been attempted. Due
to the increase of attenuation of the ultrasonic signal in the fluid
with increasing frequencies, for practical application the usable
15 frequency range is limited to a maximum of about 300 to 500 kHz. This
puts a limit on the gain that can be achieved in this way.

Special silencing devices have been designed to separate the
noise source and the ultrasonic flow meter respective to each other.
The effectiveness of such devices is limited as these devices
20 themselves may generate noise (flow induced noise) at higher gas
velocities, and again considerable costs may be involved.

Also attempts have been made to apply a variety of signal
processing techniques in order to improve the signal-to-noise ratio,
described as filtering, averaging, stacking and correlation.
25   Applying filtering techniques in the frequency domain does not
provide much improvement as the frequency spectrum of the noise often
overlaps with the operating frequency of the ultrasonic flow meter.
Typically also the ultrasonic transducers are operated in a
resonating mode in order to achieve the highest efficiency,
30 consequently the transducers themselves act as frequency selective
devices. Therefore, using additional electronic circuitry or software
for filtering the signal in the frequency domain will not be very
effective.

Improvement of the signal-to-noise ratio may be achieved by
35 increasing the amount of ultrasonic energy by extending the duration
of the burst signal. This suffers from the problem that it becomes

crossing with the aid of the shape of the envelope, or suffers from
ambiguity when phase detection techniques are used, since the travel
time to be measured represents multiple periods of the signal and the
5 phase shift is multiple times 2π.

Another known method for improving the signal-to-noise ratio is
referenced as stacking. This means averaging the signal that is
obtained by repeatedly sending and receiving an ultrasonic signal.
The assumption is that the received burst signals are correlated,
10 such that addition of multiple received burst signals results in an
increased signal, while the noise is uncorrelated and therefore will
be reduced when multiple received signals are added up. The received
signals are added taking the time of the emission as a reference
point in order to synchronise the received burst signals while these
15 are being added.

This method as well has limitations because of the natural
turbulence in gas flow. The turbulence results in a variability of
travel time (also known as "jitter") as a result of which the
received burst signals become uncorrelated. This means that using the
20 time of emission as a reference point, the received signals do not
coincide exactly when being added. The averaging or stacking
technique is therefore only effective on a short time scale: a time
scale short enough, in comparison to the periodicity of the
turbulence phenomena, to limit the variances in travel time to values
25 substantially smaller than one period of the frequency in the burst
signal. This limits the number of the received burst signals that can
effectively be added up in order to increase the signal-to-noise
ratio.

In the description of the above method the assumption has been
30 made that each cycle of emitting an ultrasonic burst signal and
receiving the same signal is completed before the next one is
initiated. A new cycle therefore can only start after the acoustic
signal has travelled across the fluid along its acoustic path, which
may take up to several milliseconds, especially for a large size
35 meter having long acoustic paths. This limits the number of pulses to
the number that can be sent within a specific time interval, i.e. the

correlated.

        As an alternative to this method, the process of sending and
receiving of acoustic pulses could be interleaved or overlapping,
5   meaning that acoustic pulses (burst signals) are being fired while
previous acoustic pulses are still travelling trough the gas. As a
result of this, a sequence of acoustic pulses will arrive at the
receiver. The problem with this alternative method, however, is to
identify each of the pulses from a sequence when they arrive, as they
10 may be heavily distorted by the acoustic noise, or even buried or
masked by the acoustic noise. Averaging the individual burst signals
within a sequence using the known repetition rate of the firing of
the pulses, will help to recover the pulse from the noise and make
the pulses detectable, but results in ambiguity. This means that the
15 burst signal may be retrieved at various points in time, while not
being able to detect which one actually represents the travel time.

        Correlation techniques are general-purpose signal processing
tools that can be applied to a variety of electronic measurements.
Major uses are the detection of the presence and the location of
20 signals buried in noise. The waveform of the signal is generally
known, for example the signal transmitted by an ultrasonic
transducer. The correlation process incrementally slides the
reference waveform over the signal being processed, looking for a
matching signal. Signals that are not related to the reference
25 waveform result in a correlation value of 0. If a matching signal is
found, the correlation value increases to a maximum value of 1 for a
perfect match and -1 for a matching but inverted waveform. The
maximum value of the correlation function serves both purposes. If
the maximum value is close to 1 the desired signal is present, and
30 the location of the maximum is a measure of the propagation delay (or
travel time).

        The application of the correlation function to the travel time
measurement in an ultrasonic meter suffers from several drawbacks. It
is computationally intensive (i.e. it requires a great deal of
35 processing power), and considering the very high time resolution that
is required for the travel time measurement, it requires very high

In view of the above drawbacks of the prior art it is an object
of the invention to provide an ultrasonic signal processing technique
that enhances the signal to noise ratio, in particular under noisy
5 circumstances.

A further object of the invention is to provide an ultrasonic
signal processing technique that allows for the unambiguous
identification of a single ultrasonic burst signal within a received
signal representing a series of subsequently transmitted burst
10 signals.

Another object of the invention is to provide an accurate
measurement of the travel time of an ultrasonic signal.

Still another object is to provide an accurate determination
method of a flow characteristic of a fluid, such as a gas or liquid,
15 for example flow velocity, using an ultrasonic measurement technique.

A still further object of the invention is to provide a device,
capable of carrying out such methods or measurements.

According to a first aspect the invention relates to a signal
processing method for improving the signal-to-noise ratio in
20 ultrasonic measurements, the method comprising transmission of a
predefined timed sequence of a number of ultrasonic burst signals at
a first transducer, wherein the time periods between subsequently
transmitted burst signals of said sequence are set according to a
non-uniform pattern, wherein at least one time period differs from an
25 other time period, and reception of a signal representing said
transmitted sequence of ultrasonic burst signals at a second
transducer, addition of multiple time-shifted copies of the received
signal to said original received signal to obtain a sum of the
original received signal and its time-shifted copies, wherein the
30 time shift of a copy is related to said predefined pattern, and
reconstruction of an original burst signal having an improved signal-
to-noise ratio from said sum.

The signal processing method according to the invention
comprises transmitting a sequence of short burst signals in a
35 relatively short time interval. In this sequence a next burst may be
transmitted before the preceding burst has arrived at the receiving

of burst signals is emitted, may overlap the time interval in which
the sequence of burst signals is received at the receiving
transducer. According to the invention the ultrasonic burst signals
5   are transmitted corresponding to a non-uniform pattern. This means
that the time period between subsequently transmitted ultrasonic
burst signals is not constant. Instead thereof at least one time
period is different from the other time periods.

While one transducer of a pair of transducers defining an
10 acoustic path, emits a sequence of burst signals, a signal
representing the sequence of burst signals received at the other
transducer is digitised and stored in a memory for further
processing. This stored signal contains the complete series of burst
signals as sent, although at first sight the individual burst signals
15 from the transmitted sequence may not be recognisable because of the
noise that is present.

The signal processing method involves creating multiple time-
shifted copies of the received signal representing the transmitted
sequence of the burst signals. The time shifts between the copies of
20 the received signal are related to the non-uniform pattern, such that
unambiguously one or more signal bursts (but preferably one) having
an improved signal-to-ratio signal can be reconstructed. As a result
of the addition, in the resulting sum a reconstructed enlarged signal
representing one signal burst from the originally transmitted
25 sequence is achieved, while the remaining part of the originally
received signal representing the noise and the other signal bursts
form the initially transmitted sequence are attenuated or cancelled.
Thus the accurate travel time of this reconstructed signal can be
measured, and used e.g. for calculation of the distance travelled or
30 a flow characteristic.

In a preferred embodiment all time periods between subsequently
transmitted signals of said sequence are different. In this
embodiment none of the time periods is the same, but they are set to
different values. For example, the time periods increase
35 incrementally with respect to the previous time period. This allows
for the reconstruction of only one burst signal from the received

total signal.

In a further preferred embodiment the number of copies is equal
to the number of burst signals in said sequence minus one, so that
the number of factors to be added, i.e. the originally received
5   signal and its copies, is equal to the total number of burst signals
in the transmitted sequence.

More preferably the time shifts are proportional, most
preferably identical, to said time periods. This means that the non-
uniform pattern is selected in such a way that in each time-shifted
10 copy of the received signal, just one burst signal out of the whole
sequence coincides with a specific one out of the originally received
signal. Adding the time-shifted copies of the sequence results in
reduction or even cancellation of the noise while the selected burst
signal that coincides every time increases in amplitude. In this way
15 the signal-to-noise ratio improves and the original single burst
signal is reconstructed, without ambiguity.

It is advantageous to reconstruct the shape of an original
burst signal, because this allows defining at least one specific zero
crossing as a reference which can be used, for example for
20 determining the travel time of the acoustic signal.

The signal processing method according to the invention has
some similarity with the "averaging" or "stacking" method discussed
above. However, in the method according to the invention the
transmitted sequence of burst signals contains specific timing
25 information that allows reconstructing a specific sample from the
sequence. The method has also some similarity to correlation
techniques, since the received signal is reconstructed using the
original transmitted signal. However in the correlation techniques a
correlation function is a function of two variables, and the result
30 needs not to have any similarity to the original burst signal,
whereas in this invention the multiple time-shifted copies are used
to reconstruct the original signal shape. The reconstructed signal
can then be used to identify a specific zero crossing as a reference
point for measuring the travel time of the acoustic signal, e.g. in
35 an ultrasonic flow meter for determining a flow characteristic of a
fluid, such as gas, in a conduit.

method according to the invention can also be used in ultrasonic distance measurement devices. In an ultrasonic distance measurement system the travel time of sequence of burst signals launched in one

5   direction by a first transducer and subsequently received by the same or another transducer is sufficient to determine the distance to be measured.

According to a second aspect the invention relates to a method of determining a flow characteristic of a fluid in a conduit using an

10   ultrasonic measurement device, comprising transmitting a predefined timed sequence of a number of ultrasonic burst signals at a first transducer, such that the time periods between subsequently transmitted burst signals of said sequence are set according to a non-uniform pattern, and receiving a signal representing said

15   sequence of ultrasonic burst signals at a second transducer, adding multiple time-shifted copies of the received signal to obtain a sum of the original received signal and its time-shifted copies, wherein the time shifts are related to said predefined pattern, reconstructing an original burst signal, determining the travel time

20   of said reconstructed original burst signal, and calculating the flow characteristic using said travel time. Because in this method according to the invention the principles of the ultrasonic signal processing method according to the invention as discussed above are applied, the original burst signal can be reconstructed accurately

25   and unambiguously, with the result that the travel time can be calculated accurately, as well as the flow characteristic related to this travel time. Examples of such a flow characteristic are flow velocity and flow throughput, energy content of a fuel gas such as natural gas, and the like.

30   The above identified preferred embodiments of the signal processing method according to the invention are likewise applicable to this second aspect of the invention.

A further aspect of the invention is directed to a device for determining a flow characteristic of a fluid in a conduit, comprising

35   ultrasonic transmission means for providing a predefined timed sequence of a number of ultrasonic burst signals for injection into

burst signal of said sequence according to a predefined non-uniform
pattern, ultrasonic reception means for receiving a signal
representing said sequence of ultrasonic burst signals, and signal
5   processing means for processing said signal in order to determine the
flow characteristic from said signal, wherein the signal processing
means comprise means for providing multiple time-shifted copies of
the received signal which copies are time-shifted according to a
predefined relationship with said non-uniform pattern, and for adding
10   the multiple time-shifted copies of the received signal to the
received signal, and for reconstructing an original burst signal, and
for calculating the flow characteristic using said reconstructed
original burst signal.

In this device according to the invention the signal processing
15   means are designed in such a way that a number of time-shifted copies
of the received are created. These copies are added to the originally
received signal. From the sum an originally fired burst signal is
obtained, from which in turn the desired flow characteristic is
calculated. For example, the flow velocity can be obtained from the
20   difference in travel time of a sequence of burst signals transmitted
in the direction of the flow (downstream) and of a sequence of burst
signals transmitted in the opposite direction (upstream).

Preferably the means are designed such that the means allow
performing the preferred embodiments of the method according to the
25   invention as described above.

The invention is further illustrated by means of the attached
drawings, in which:

Figure 1 shows the basic elements of a single-path ultrasonic
flow meter;
30   Figure 2 is a block diagram of an ultrasonic flow meter
according to the invention;

Figure 3 shows the transmitted and received waveforms of an
ultrasonic flow meter according to the prior art;

Figure 4 shows the transmitted and received waveforms according
35   to the invention; and

Figure 5 shows the processed waveforms according to the

invention.

Figure 1 shows the basic elements of an example of a flow
measurement system for determining the fluid flow in a cylindrical
conduit 1. From a pair of transducers 2a, 2b, each one is connected
5 by electrical leads 4a and 4b respectively to a signal processing
unit identified in its entirety by reference numeral 100. The
transducers 2a, 2b are positioned such that they define an
interrogation path 3 with precisely defined geometric dimensions. The
interrogation path shown in Figure 1 is a bounce-type centerline
10 path. However, other arrangements of transducers and path
configurations are possible, e.g. an inscribed triangle (having two
bounces against the wall of the conduit).

Figure 2 is a block diagram of an ultrasonic flow meter
according to the present invention. A pair of transducers 2a, 2b is
15 mounted on a conduit 1, defining an interrogation path 3. The
transducers 2a, 2b are connected by electrical leads 4a, 4b to both a
signal generator 5 and a signal receiver 11. The signal generator 5
is controlled by a timing and control unit (TCU) 21 via control and
data bus 22 to provide the one or more transducers 2a, 2b with an
20 ultrasonic signal at defined instants in time. The transmit signal
itself is calculated by a digital signal processor (DSP) 23 and
loaded into the signal generator's RAM 7 by means of direct memory
access (DMA) 6. Controlled by the TCU 21 the signal generator 5
shifts the transmit signal stored in RAM 7 sequentially to digital-
25 to-analogue converter (DAC) 8. The output of DAC 8 is amplified by
power amplifier 9. A transmit multiplexer 10 provides one or more
transducers 2a, 2b with the ultrasonic signal to be transmitted.

The transducers 2a, 2b are also connected to the signal
receiver 11. The signal receiver 11 consists of buffers/preamplifiers
30 12a, 12b and a receive multiplexer 13. Similarly to the signal
generator 5, the signal receiver 11 is controlled by the TCU 21 to
provide the appropriate transducer signals to a signal amplifier 14.
The signal amplifier 14 is controlled by an automatic gain controller
(AGC) 16. The amplified signal is then digitised by the signal
35 converter 17. Controlled by the TCU 21 the analogue-to-digital
converter (ADC) 18 writes the sampled signal to a RAM 19. The

(DMA) 20. The digital signal processing unit DSP 23 processes the sampled data of RAM 19 according to the invention. Data at various processing stages can be made available at the user interface by
5   means of input/output unit 24.

Figure 3 shows the transmitted and received waveforms of a conventional ultrasonic flow meter.

Figure 3a shows an example of a transmitted waveform of an ultrasonic transducer with a center frequency of approximately 200
10   kHz and a bandwidth of approximately 40 kHz. The impulse response (Y-axis) of a transducer 2a, 2b is shown as a function of time (X-axis; seconds).

Figure 3b shows the waveform of figure 3a, but "zoomed in" to about 10 cycles (of the 200 kHz transducer frequency) both before (t
15   < 0) and after (t > 0) triggering the transducer.

Figure 3c shows the received waveform at moderate signal-to-noise ratio. The signal propagation time between a pair of transducers is 1 millisecond (ms).

Figure 3d shows the waveform of figure 3c, but "zoomed in" to
20   about 10 cycles of the 200 kHz transducer frequency both before and after the propagation delay. The received waveform shows good conformity with the transmitted waveform. Various methods are applicable to the detection of the presence of this waveform and the estimation of the propagation delay, including very simple ones like
25   thresholding the signal.

Figure 3e shows the received waveform at very low signal-to-noise ratio. Again the signal propagation time is 1 millisecond (ms). It is apparent that the waveform of the originally transmitted signal is completely obscured by noise. Thus, it is not possible to detect
30   the presence and the propagation delay of the transmitted signal.

Figure 4 shows the transmitted and received waveforms according to the invention.

Figure 4a shows a sample transmitted waveform consisting of 8 individual bursts having waveforms similar to the transmit waveform
35   of figure 3a and 3b. In other words the sequence consists of 8 ultrasonic burst signals. In this example of the invention the

i.e. all spacings are different.

Figure 4b represents the waveform of figure 4a, but again "zoomed in" to show the individual wavelets or ultrasonic burst
5   signals and associated spacings in more detail.

Figure 4c shows the received waveform at very low signal-to-noise ratio (comparable to the signal-to-noise ratio as shown in figure 3e). The propagation delay is 1 millisecond (ms). Much like the situation depicted in figure 3e, in the signal as received the
10 transmitted individual wavelets are obscured by noise.

Figure 4d shows the waveform of figure 4c, but "zoomed in" to about 10 cycles (of the 200 kHz transducer frequency) both before and after the propagation delay.

Figure 5 shows the waveforms, as processed according to the
15 invention.

In Figure 5a the topmost trace is identical to the received waveform shown in figure 4c. The 7 traces below the topmost trace are time-shifted copies of the received waveform. The time shifts are identical to the spacings of the transmitted individual wavelets
20 (Figure 4a and 4b). The bottom trace is the sum of the original received waveform and its time-shifted copies.

Figure 5b shows the same processed waveform as shown by the bottom trace of figure 5a: the sum of the original received waveform and its time-shifted copies. This processed "received" waveform has
25 all the characteristics of the received waveform resulting from the transmission of a single wavelet, but at improved signal to noise ratio.

Figure 5c shows the waveform of figure 5b, but "zoomed in" to about 10 cycles (of the 200 kHz transducer frequency) both before and
30 after the propagation delay.

It is apparent that the signal processing method according to the invention results in the reconstruction of a burst signal out of the originally transmitted series, which is not masked, buried or otherwise obscured by noise or other transmitted burst signals from
35 the series. The travel time of this reconstructed signal can be determined accurately.